

DSMS Telecommunications Link
Design Handbook

211

Wideband Very-Long Baseline Interferometry


Released August 25, 2006

Document Owner:

Approved by:


Alina Bedrossian
Radio Science
System Engineer

Date


Timothy T. Pham
DSN Chief System Engineer

Date

Author:

Released by:


Peter W. Kunin
8/3/2006

Signature on file at DSMS Library 8/25/06
DSMS Document Release Date

Change Log

Rev	Issue Date	Affected Paragraphs	Change Summary
Initial	8/25/2006	All	All

Note to Readers

There are two sets of document histories in the 810-005 document, and these histories are reflected in the header at the top of the page. First, the entire document is periodically released as a revision when major changes affect a majority of the modules. For example, this module is part of 810-005, Revision E. Second, the individual modules also change, starting as an initial issue that has no revision letter. When a module is changed, a change letter is appended to the module number on the second line of the header and a summary of the changes is entered in the module's change log.

Contents

<u>Paragraph</u>	<u>Page</u>
1 Introduction	4
1.1 Purpose.....	4
1.2 Scope.....	4
2 General Information.....	4
2.1 Description of Very-long Baseline Interferometry	4
2.2 Bandwidth Synthesis	6
2.3 DSN VLBI Support Equipment	7
2.3.1 Signal Reception	8
2.3.2 Subreflector Position.....	9
2.3.3 Data Acquisition	9
2.3.4 Phase Calibration Tones.....	10
2.3.5 Correlation.....	11
2.4 Experiment Design	11
3 References	13

Illustrations

<u>Figure</u>	<u>Page</u>
1. Very Long Baseline Interferometry	5
2. DSN Equipment for Wideband VLBI Support.....	8

Tables

<u>Tables</u>	<u>Page</u>
1. Frequency and Polarization Support Capabilities for VLBI.....	9
2. Typical Channels (S and X Bands) for Wideband VLBI	12

1 Introduction

1.1 Purpose

This module provides an introduction to the Very-Long Baseline Interferometry (VLBI) astrometric measurement technique and identifies the capabilities and performance of Deep Space Network (DSN) equipment used to support wideband VLBI measurements.

1.2 Scope

The content of this module is limited to a discussion of the data gathering and data processing equipment used by the DSN to support VLBI. Experiment design and the quality of the results are influenced by many other factors that are discussed elsewhere in this handbook. Among these factors are antenna performance parameters discussed in modules 101, 103 and 104, and frequency reference performance discussed in module 304. VLBI experimenters may also be interested in station locations discussed in module 301 and extra-galactic radio source positions provided by module 107. It should be noted that the equipment discussed in this module is the major contributor to the information content of modules 301 and 107.

2 General Information

The DSN uses its VLBI capability to measure the earth orientation parameters that establish the relationship of the Terrestrial Reference Frame containing its stations to the Celestial Reference Frame used for spacecraft navigation. VLBI is also used to verify the relative locations of its stations and to corroborate the locations of extra-galactic radio sources (EGRSs). The EGRSs are used as fiducial reference points for delta-differential one-way ranging (Δ DOR) spacecraft navigation (see module 210). Because the DSN has used the same equipment as the international VLBI community since the creation of the original standard Mark III VLBI Data Acquisition Terminal (Reference 1), other agencies can coordinate their observation schedules with DSN scheduled activities and the resultant data can be shared between the DSN and external experimenters.

2.1 Description of Very-Long Baseline Interferometry

Very-Long Baseline Interferometry is a technique for measuring the precise time difference between the arrival of a waveform originating from an EGRS at two (or more) stations. Figure 1 provides an illustration of the technique. The stations simultaneously observe an EGRS. As they are widely separated, their baseline, B , passes through the Earth. At each station, the instantaneous phase of the received signal (a random Gaussian process) is recorded in each of several channels; this is known as VLBI data acquisition. The measured difference in arrival time can be converted to an approximate path length difference by multiplying by c , the speed of electromagnetic waves in a vacuum. In actuality, the conversion is much more complex as the wave front must pass through several layers of the Earth's atmosphere – each of which has a different propagation speed.

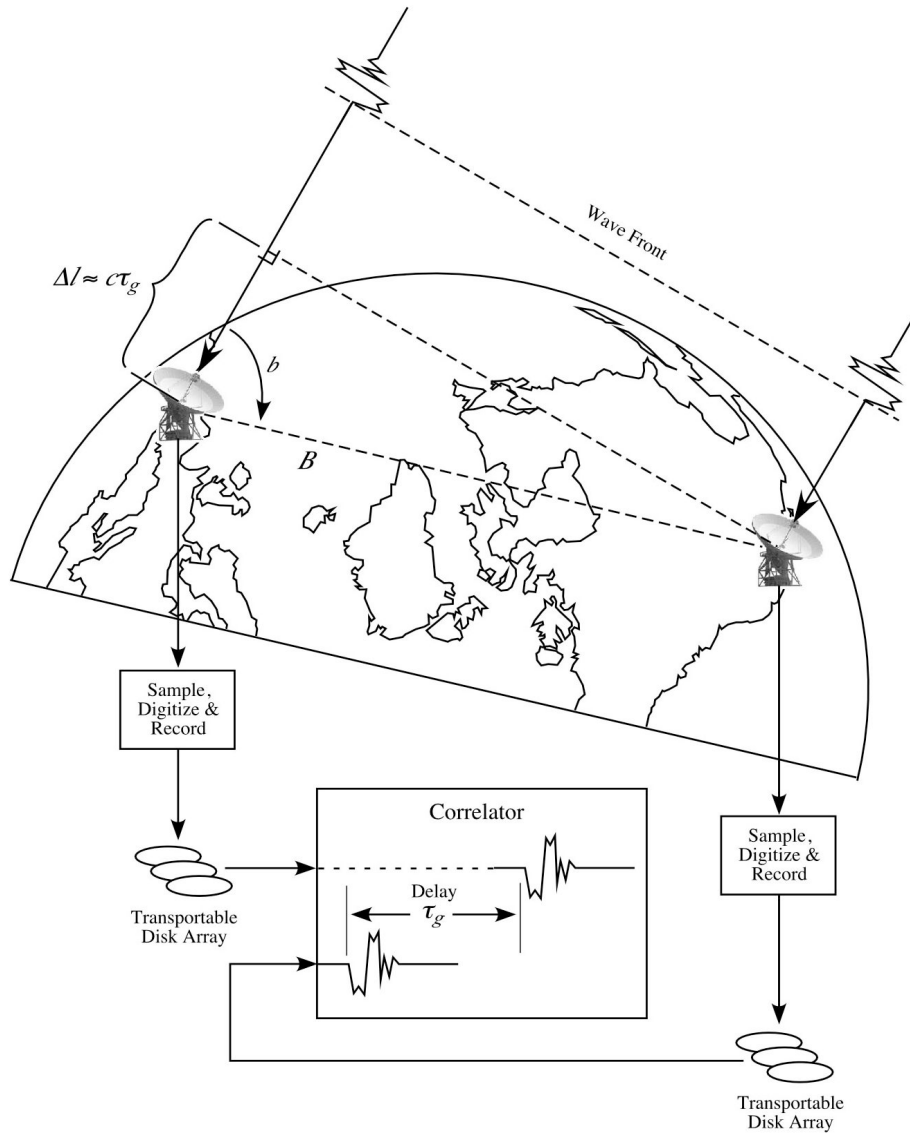


Figure 1. Very-Long Baseline Interferometry

The recorded data from the participating radio telescopes are brought together. The data from matching channels at the different radio telescopes are cross-correlated to determine the geometric time delay, τ_g ; this is known as VLBI data correlation. After converting the time delay to a path length by a process that takes into account atmospheric delay and other effects, the angular relationship between the baseline of the two stations and the radio source can be determined by the relationship $b = \cos^{-1}(\Delta/B)$. It is important to note that this is not a complete solution for the angular position in the sky of the radio source. This calculation only provides information about the location of the radio source in the plane defined by the interferometer baseline and the direction of arrival. The correlation of data from the observation of additional radio sources is necessary to completely define the baseline. By making sufficient

observations and assuming some reference, it is possible to calculate a singular solution that estimates each station's coordinates, the angular position of all observed sources, the offset and rate differences between the two station frequency references, and several parameters relating to propagation. Additional observations above the minimum enable statistical uncertainties in the estimation to be reduced. A complete discussion of the process is contained in Reference 2.

The precision of a VLBI measurement improves with the length of the baseline. The location of the DSN stations provides baselines of 66% (Goldstone to Madrid) and 83% (Goldstone to Canberra) of the Earth's diameter. The third baseline, Canberra to Madrid, is 98% of the Earth's diameter but provides very limited mutual visibility (see module 301). To mitigate mutual visibility effects, additional radio telescopes are often involved in VLBI measurements allowing a station between DSN locations to serve as a "relay" to tie-together observations made in different portions of the sky during an observation session.

2.2 *Bandwidth Synthesis*

The signal-to-noise ratio obtained by correlating the signals from two observing stations depends on the characteristics of the stations, the bandwidth of the channel being correlated and the observation time. It can be calculated from the following expression (Reference 3).

$$SNR_{CH} = 2.05 \times 10^{-4} (\gamma_v S) D_1 D_2 \sqrt{\frac{\eta_1 \eta_2 B_{CH} T}{T_{Sys1} T_{Sys2}}} \quad (1)$$

where

$(\gamma_v S)$ = correlated flux density where S is the total flux density (jansky)

D_1, D_2 = antenna diameters (m)

η_1, η_2 = antenna efficiencies

B_{CH} = channel bandwidth (Hz)

T = observation time (s)

T_{Sys1}, T_{Sys2} = antenna system noise temperatures (K)

The factor 2.05×10^{-4} includes all normalization constants and allowances for degradation due to one-bit quantization and the fact that only one polarization is received.

When multiple channels are being correlated simultaneously and they have approximately the same SNR_{CH} , the post-correlation SNR for use in equation (3) can be calculated by

$$SNR = \sqrt{n} \cdot SNR_{CH} \quad (2)$$

where n is the number of channels in the correlation.

The error in delay measurement resulting from the correlation of data from two VLBI stations is expressed by

$$\sigma = \frac{c}{2\pi \cdot SNR \cdot BW} \quad (3)$$

where

c = the speed of electromagnetic propagation

SNR = the post-correlation signal-to-noise ratio

BW = the observation bandwidth

It can be seen from equation (3) that an extremely large data volume for transport to the common correlation site would be needed if the entire bandwidth were recorded. For example, if a post-correlation SNR of 40 (16 dB) is available, a bandwidth of 125 MHz would be required to achieve a delay error of 1 cm.

The data volume is significantly reduced by the technique of *bandwidth synthesis* (Reference 4). This technique uses several narrow channels spread across the observation bandwidth to achieve an *RMS bandwidth* of

$$BW_{RMS} = \sqrt{\frac{\sum_{CH=1}^n (f_{CH} - f_{AVG})^2}{n}} \quad (4)$$

where

f_{CH} = center frequency of each channel used in the bandwidth synthesis

f_{AVG} = the average of all channel center frequencies used in the bandwidth synthesis

n = the number of channels

As an example of the efficiency gained by bandwidth synthesis, a typical X-band VLBI measurement will use the eight 2-MHz channel pairs shown in Table 2 corresponding to an RMS bandwidth of 140 MHz. By employing hard limiting, one-bit quantization, and a sampling rate equal to twice the bandwidth of each channel, the total recorded bandwidth is reduced to 64 MHz.

2.3 DSN VLBI Support Equipment

A diagram showing the major items of DSN equipment used to support wideband VLBI is provided by Figure 2. All DSN 34-m HEF antennas and 70-m antennas are available for VLBI data acquisition. In addition, some 34-m BWG antennas have been used for VLBI.

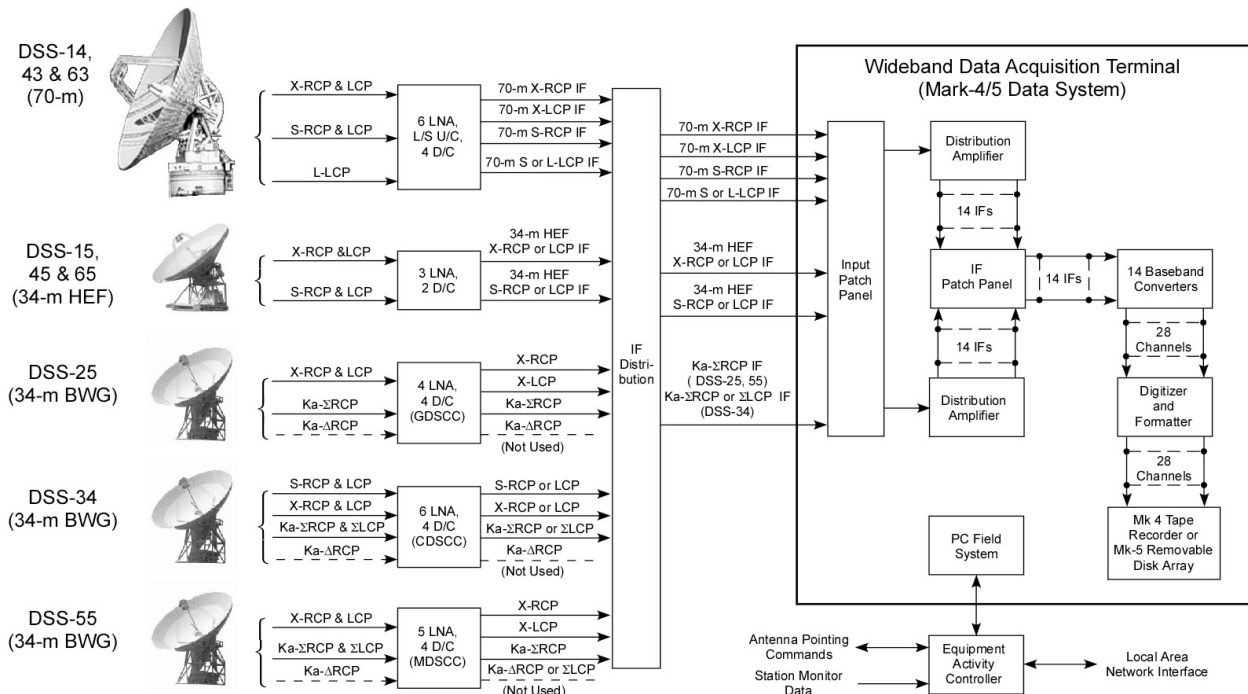


Figure 2. DSN Equipment for Wideband VLBI Support

Received signals are processed by a standard Mark-IV/Mark-V Data Acquisition Terminal (DAT). An Equipment Activity Controller (EAC) provides the interface between the DAT's PC Field System and the DSN subsystems.

2.3.1 Signal Reception

Signals that are collected by the antenna are amplified by a cryogenically-cooled low-noise amplifier (LNA). For every observation band except L, the LNA is followed by a downconverter that translates the radio-frequency signal to an intermediate frequency (IF) to be forwarded to the Signal Processing Center (SPC). The downconverters are located on the antenna and are derived from the station frequency standard. Their frequencies are 2.0 GHz for S band, 8.1 GHz for X band, and 31.7 GHz for Ka band. The L-band signal at a 70-m antenna is upconverted to S-band using a 620-MHz local oscillator and then switched into one of the S-band downconverters. From that point forward, it follows the same path normally taken by a signal originating in the S band.

DSS-25 at the Goldstone DSCC, DSS-34 at the Canberra DSCC, and DSS-55 at the Madrid DSCC are available for Ka-band VLBI support. However, the Ka-band configuration of each of these antennas is somewhat different. The Ka-band feed of DSS 25 supports RCP but does not support LCP. DSS-34 supports both RCP and LCP and is capable of routing either polarization to the VLBI data acquisition equipment. DSS-55 supports both polarizations but only the RCP signal is available for VLBI. The frequency and polarization capabilities of the DSN for VLBI are summarized in Table 1.

Table 1. Frequency and Polarization Support Capabilities for VLBI

Subnet or Station	L-band	S-band	X-band	Ka-band
70-m subnet (DSS-14, 43, & 63)	LCP(1) (1628–1708 MHz)	RCP and LCP (2200–2300 MHz)	RCP and LCP (8400–8500 MHz)	–
34-m HEF subnet (DSS-14, 43, & 63)	–	RCP or LCP (2200–2300 MHz)	RCP or LCP (8200–8600 MHz)	–
34-m BWG, DSS-25	–	–	(2)	RCP (31.8–32.3 GHz)
34-m BWG, DSS-34	–	(2)	(2)	RCP or LCP (31.8–32.3 GHz)
34-m BWG, DSS-55	–	(2)	(2)	RCP (31.8–32.3 GHz)

- (1) L-band cannot be used simultaneously with any other band.
(2) Received but not routed to VLBI data acquisition terminal.

2.3.2 Subreflector Position

Gravity deformation of the primary reflector and the structure that supports the subreflector as the antenna moves in elevation causes a change in the antenna focal position. To compensate for this, the subreflector undergoes a programmed motion relative to the feed to achieve the maximum antenna gain at every elevation angle. However, this motion introduces a time-varying phase delay to the received signal that is undesirable for wideband VLBI.

During wideband VLBI data acquisition at the 34-m HEF and 70-m antennas, the subreflector motion is usually disabled and the subreflector placed in a position that gives the best gain for a 45° elevation angle. This eliminates the time-varying phase delay associated with subreflector motion. However, it also causes some loss of antenna gain when the antenna is not at 45°.

Subreflector motion should not be disabled when a BWG antenna is used for wideband VLBI observations in the Ka band. This is because gravity deformation also affects antenna pointing to an amount that is significant at Ka-band although not so at S- or X-bands and subreflector motion must be enabled in order to have the antenna point as commanded. The resultant phase delay changes can be modeled and removed in post processing

2.3.3 Data Acquisition

The Mark-IV and Mark-V configurations of the DAT only differ in the way the data are recorded. The remaining equipment is the same. The antenna IFs are supplied to a patch panel where any two of them can be selected as the DAT's input. Either of these two IFs can be routed to each of 14 baseband converters. The baseband converters mix the IF with a local oscillator derived from the station frequency standard using the single-sideband mixing

technique to avoid spectrum fold-over (Reference 5). The result is two filtered baseband channels corresponding to the upper and lower sidebands centered about the local oscillator frequency. The local oscillator frequency and filter bandwidth of each baseband converter can be set independently with bandwidths of 2.0, 4.0, 8.0 and 16.0 MHz available for each converter. Bandwidths of 125 kHz and 500 kHz are available in some video converters. A fifteenth baseband converter is included in the DAT as a spare or for use as a test signal generator.

The outputs of the baseband converters are routed to a formatter where they are digitized using one-bit digitization, placed into recording frames along with timing and parity data, and sent to a tape recorder in the Mark-IV configuration or one or two disk arrays in the Mark-V configuration. The recorders can record up to 28 data tracks in one direction or 14 tracks in the forward direction and 14 tracks in the reverse direction. Placement of the recorder's playback head makes read-after-write verification possible when recording in the forward direction. The disk array (Reference 6) was designed to be a direct replacement for the Mark IV tape unit but is limited to saving the data from a maximum of 16 tracks. All 28 tracks can be recorded when two disk arrays are used.

2.3.4 *Phase Calibration Tones*

The 34-m HEF and 70-m antennas include phase calibration generators (PCGs) for all of their supported frequency bands (Reference 7). The PCGs inject a set of tones, uniformly spaced in frequency, into the receive signal path ahead of the LNA. The purpose of these tones is to permit calibration of irregularities in phase delay occurring along the signal path to the DAT and phase differences within the DAT resulting from each video converter having a separate local oscillator. The tones are spaced 1.0 MHz apart and are derived from the station frequency reference. The power in the phase calibration tones is less than 1% of the signal power in any given bandwidth. With such a small power, the phase calibration tones do not interfere with the VLBI measurements. The 1.0 MHz spacing guarantees that at least one tone will be present in each 2-MHz or greater bandwidth normally used for VLBI. Selection of channel center frequencies will assure that one tone will be present in one sideband of each channel for narrower bandwidths. DSS 25 has a prototype Ka-band PCG with tone spacing that may be selected as either 5.0 MHz or 1.0 MHz. The tones are derived from the station frequency reference as is the case with the standard phase calibrators.

In the VLBI correlator, a measurement is made of the relative phase delay of the calibration tone in each channel. This is accomplished by correlating the recorded channel with a local (baseband) model of the individual calibration tone. These phase delay measurements enable the phase slope of the entire instrumentation system to be estimated and any phase offsets introduced into the individual channels within the DAT to be removed. The result is a group delay calibration with a precision of 0.0015 ns for a 100-s integration time.

In addition to the precise measurement of phase delay in post processing at the VLBI correlator, the phase calibration tones are also monitored in real-time by a digital tone extractor (DTE) to detect instrument and configuration problems.

2.3.5 *Correlation*

The JPL VLBI correlator accepts VLBI data in Mark IV or Mark V format. The recorded data from as many as four radiotelescopes may be cross-correlated. When the recorded data from one radiotelescope is cross-correlated with that of another radiotelescope, an interferometer is formed and the differential delay for that interferometer is determined. As many as six interferometers can be formed with recorded data from four radiotelescopes.

2.4 *Experiment Design*

The configuration and sequence of events for any wideband VLBI experiment are defined in a VLBI experiment (VEX) file. The VEX file is a format invented by members of the VLBI community to prescribe a complete description of a VLBI experiment, including scheduling, data-taking and correlation. Parameters from this file are read by the Personal Computer Field System (PCFS) and are translated to the necessary antenna pointing and other commands needed to operate DSN equipment by the Equipment Activity Controller (EAC). The EAC also subscribes to DSN monitor data to deliver ancillary data to the PCFS for inclusion in the experiment log file.

The one or two observation bands (L, S, X or Ka) for the experiment are chosen subject to the band availability on the antenna being used. A set of channels is defined for each observation band. In order to achieve high precision, the span of channel frequencies (within the band) should be wide. The two outermost channels determine this precision. The other channels are needed to resolve the phase ambiguity. Simultaneous measurements at S- and X-band enable the differential delay in the ray path to the two observing stations caused by the Earth's ionosphere to be calibrated (Reference 2).

The channels are defined in pairs. A channel pair is created within each video converter, whose local oscillator determines the center frequency of the pair. At each complex, up to 14 video converters may be used simultaneously resulting in a maximum of 28 channels. Each of the 14 channel pairs is assigned to one or the other observation band. A typical set of channel-pair frequencies is shown in Table 2 for simultaneous observation in the S and X bands. Also shown in Table 2 is the local oscillator frequency for the video converter that produces the corresponding channel-pair frequency. It may be noticed that the channel-pair frequency equals the local oscillator frequency of the video converter plus that of the first downconverter (2.0 GHz for S band and 8.1 GHz for X band).

Each channel is digitized with one-bit quantization and a selectable sampling rate. When scheduling an observation, users normally employ a template that helps them choose sampling rates that are consistent with the bandwidths selected for the video converters. The resultant parallel digital streams are formatted, time-tagged and recorded in the Mark IV (tape) or Mark 5 (disk array) format.

Table 2. Typical Channels (S and X Bands) for Wideband VLBI

Channel Pair	Video Converter Local Oscillator
2217.99 MHz LSB & USB	217.99 MHz
2222.99 MHz LSB & USB	222.99 MHz
2237.99 MHz LSB & USB	237.99 MHz
2267.99 MHz LSB & USB	267.99 MHz
2292.99 MHz LSB & USB	292.99 MHz
2302.99 MHz LSB & USB	302.99 MHz
8210.99 MHz LSB & USB	110.99 MHz
8220.99 MHz LSB & USB	120.99 MHz
8250.99 MHz LSB & USB	150.99 MHz
8310.99 MHz LSB & USB	210.99 MHz
8420.99 MHz LSB & USB	320.99 MHz
8500.99 MHz LSB & USB	400.99 MHz
8550.99 MHz LSB & USB	450.99 MHz
8570.99 MHz LSB & USB	470.99 MHz

3 *References*

1. A. E. E. Rogers and T. A. Clark, "The Mark III Data Acquisition Terminal," Crustal Dynamics Project, Goddard Space Flight Center, Greenbelt, Maryland, January 1982.
2. O. J. Sovers, J. L. Fanelow, and C. S. Jacobs, "Astrometry and Geodesy with Radio Interferometry: Experiments, Models, Results," *Reviews of Modern Physics*, Vol. 70, No. 4, The American Physical Society, October, 1998
3. G. S. Parks, R. W. Sniffin, S.C. Wu, J.B. Thomas, "Operational Mobile VLBI Data Acquisition System (MV-3) Design Requirements," *JPL Internal Document 1700-11*, Jet Propulsion Laboratory, Pasadena, CA, December 1, 1982
4. A. E. E. Rogers, "Very long baseline interferometry with large effective bandwidth for phase-delay measurements," *Radio Science Volume 5, Number 10*, pp. 1239–1247, October 1970.
5. N. C. Ham, "Frequency Down-Converters as Applied to VLBI," *DSN Progress Report 42-53*, Jet Propulsion Laboratory, Pasadena, CA, October 15, 1979.
6. A. R. Whitney, "Mark 5 Disk-Based Gbps VLBI Data System," in *New Technologies in VLBI*, edited by Y. C. Minh, ASP Conference Series, Vol. 306, Astronomical Society of the Pacific, San Francisco, CA, 2003.
7. R. Hamell, B. Tucker, M. Calhoun, "Phase Calibration Generator," *IPN Progress Report 42-154*, Jet Propulsion Laboratory, Pasadena, CA, October 15, 2003.